Mars Global Surveyor: Aerobraking Mission Overview

by

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Abstract:

The **Mars Global Surveyor** spacecraft was launched on November 6, 1996 and was captured into a highly elliptical, 45 hour orbit around **Mars** with a 973 m/s propulsive maneuver on September 12, 1997. A four month **aerobraking** phase was supposed to remove another 1200 m/s in order to circularize the orbit. Unfortunately, one of the two solar wings was damaged during deployment just after launch when the deployment damper failed. This paper will describe what has happened so far in order to achieve the original mission objectives and will discuss the plans for the future of the Mars Global Surveyor Spacecraft.

A Brief History:

Immediately after launch, telemetry indicated that one of the two solar wings had failed to latch. Each of the two Mars Global Surveyor spacecraft wings is comprised of two solar panels and a drag flap (as shown in Figure 1). The preliminary failure model that explained the post-launch solar panel deployment anomaly was that the damper shaft had sheared off during deployment.[1] The arm that turned the shaft was believed to be wedged between the inner panel and the yoke and was preventing the panel from latching. Figure 2 shows the position of the panel in the stowed and partially deployed positions with the damper arm still attached to the damper, and also in the initially deployed configuration, with the damper arm pinched between the yoke and the inboard panel. Figure 2 shows that placing the damper arm between the yoke and the panel would put the panel 24.6° from the fully latched position. Since the actual angle was only 20.5°, the project analysts concluded that the sharp end of the damper arm had penetrated a short distance into the

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inboard panel when the panel deployment was abruptly terminated when the damper arm contacted the yoke. An extensive analysis was conducted during the cruise to Mars to both understand the failure and to redesign the aerobraking phase that was scheduled to begin immediately following Mars Orbit Insertion (MOI). The primary outcome of the redesign effort was that the spacecraft was reconfigured for aerobraking, as shown in Figure 1, such that the failed wing (on the -Y side of the spacecraft) was rotated 180° using the inner gimbal in order to put the active side of the panels on the damaged wing into the flow during each drag pass through the atmosphere. The outer gimbal position was also changed in order to maintain the same aerodynamic configuration with the solar wings swept back by 30°. The reconfiguration was necessary so that the aerodynamic torque at the hinge line would push the hinge toward the closed position, because the deployment springs were not strong enough to hold the panel in position against the drag induced torque about the hinge line.

Minor changes to the sequencing software were required to use a powered mode to hold the outer gimbal in position, rather than the unpowered mode that was still used on the undamaged wing, where the gimbal could be positioned next to a hard-stop. The gimbal motor had to be requalified for the higher holding torque required for aerobraking in the new configuration. The solar cell sides of the -Y panels had to be requalified at a higher temperature to demonstrate that the cells that would now be directly exposed to the aerodynamic flow could withstand the higher temperatures on the leading side of the wing. Since the gimbal was able to supply sufficient torque, and since the cells could withstand the higher temperatures, the basic aerobraking trajectory remained targeted to the originally planned 400 km circular, Sun-synchronous 2 pm mapping orbit[2].

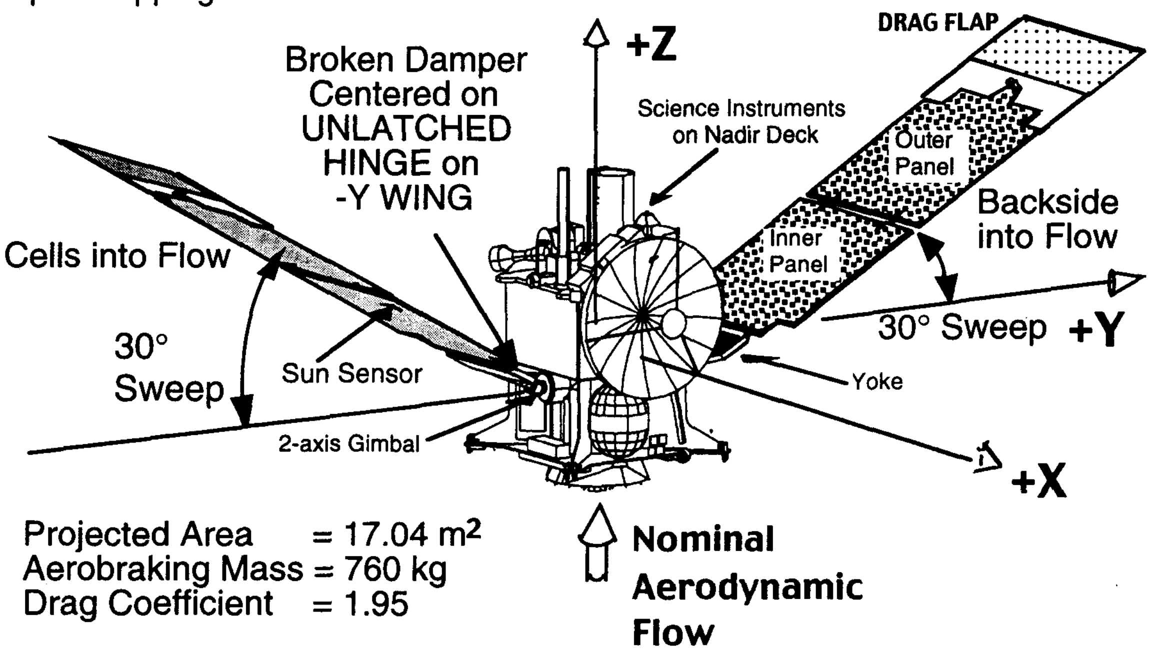

Figure 1: Mars Global Surveyor Aerobraking Configuration

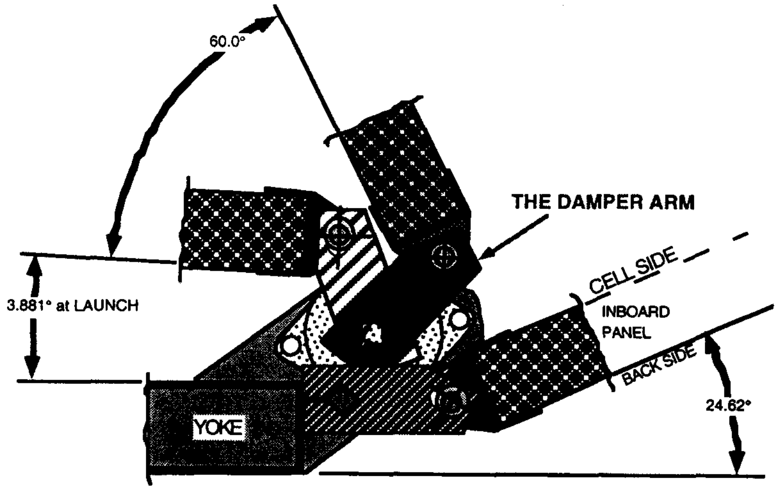

Figure 2: Detail of the Broken Solar Panel Damper Assembly

The panel positions for maneuvers using the main engine also had to be changed to minimize the moment around the hinge line to prevent the unlatched panel from shifting during these maneuvers. The capture orbit period was retargeted from 48 hours to 45 hours to reduce the average dynamic pressures and aerodynamic heating required during aerobraking. The periapsis altitude target at capture was reduced from 313 km to 250 km to minimize the ΔV required at MOI. The reconfiguration worked as planned, and the Mars Global Surveyor was captured into a highly elliptical orbit around Mars by a 973 m/s main engine maneuver on September 12, 1997. The actual periapsis altitude of 262.9 km was only 12.9 km higher than the 250 km target, while the actual 44.993 hour orbit period at the first apoapsis was within 25 seconds of the 45 hour target . All of the analyses, testing, requalifications, planning, and software updating had to be completed prior to MOI.

Aerobraking Begins with Redesigned S/C Configuration:

Aerobraking began on schedule three orbits after MOI, and proceeded as replanned through Orbit# 15. The time between the propulsive Walkin maneuvers used to lower the periapsis altitude from the high altitude capture orbit down to the altitude required for aerobraking was reduced so that the main phase of aerobraking would begin earlier than the original plan. Starting the main phase earlier further reduced the average dynamic pressures and aerodynamic heating.

At MOI, the project analysts believed that the only problem was that the –Y wing was not fully latched. During these early aerobraking orbits, some panel deflection was inferred from the attitude telemetry, but was attributed to elastic defomation near the location where the damper arm was wedged between the yoke and the inner panel of the unlatched wing. Since the panel was not latched, some deflection had been predicted by the structural analyses. There was a moderate uncertainty in the magnitude of the deflection, especially during the early orbits where the amount of deflection was small. The deflection was inferred from the difference between the expected location of the aerodynamic 3 attitude and the observed aerodynamic null[3]. (The aerodynamic null is the attitude where the aerodynamic moments about the X and Y axes are simultaneously zero.) Other possible contributors to a shift in the aerodynamic null included cross-wind, surface accommodation differences between the back of the +Y wing and the cell-side of the -Y wing, flexing or asymmetry in the flaps at the ends of the solar wings, and unmodelled asymmetries in the spacecraft configuration. As the dynamic pressure increased, the apparent offset in the aerodynamic null also increased, as would be expected if one of the panels were connected to the spacecraft through a spring with a stiffness of about 1100 in-lb/radian.

On orbit# 11 accelerometer telemetry near the time of periapsis indicated that the damper arm appeared to shift when the maximum dynamic pressure was pushing on the spacecraft. Telemetry from a Sun sensor mounted on the inner panel of the unlatched wing confirmed that the panel had moved 4° closer to the latched position. Near the maximum dynamic pressure on the next orbit, the unlatched solar wing shifted again, this time by 15°, such that the panel offset was reduced to nearly zero. The outer gimbal position of the damaged wing was commanded to a new position after each shift to maintain a symmetric aerodynamic configuration with a 30° sweep angle to the flow for the next drag pass.

The operations team briefly considered that the panel might have latched into position until the telemetry data from the next orbit indicated that the aerodynamic null perturbation that had been attributed to panel bending was still present. The shifts in the solar panel position implied that the damper arm had moved out from between the yoke and the inner panel such that the hinge had reached the latched position. Since the postulated hinge configuration was such that the wing could not possibly bend about the hinge line beyond the latched position, but the data indicated that the panel was bending beyond the latched position, the failure mode had to be different than the one established during cruise. The project analysts immediately began to examine the telemetry to develop a new failure model that could explain the new data. Possible failure mechanisms were discussed during the next three orbits, while aerobraking continued as planned.

On orbit# 15, three orbits after the 20.5° kink in the unlatched panel straightened out, the atmospheric density was unusually high (50% larger than on the previous two orbits - see Table 1) and the panel deflection inferred from the dynamic changes in the aerodynamic null implied a huge, 17° deflection. Since the magnitude of the deflection on orbit# 15 could not possibly be explained by the original failure model, the Project Manager concluded that the solar wing was not only unlatched, but also damaged more seriously than originally believed. A command was immediately sent to propulsively raise the periapsis altitude by 11 km in order to reduce the dynamic pressure from 0.60 to 0.20 N/m^2, and thus reduce the apparent bending to a few degrees. The attitude for the drag pass on orbit# 16 was changed so that the Sun sensor mounted on the unlatched wing could be used to measure the position of the Sun relative to the solar panel during the drag pass, and confirm if the solar wing was bending relative to the inertially propagated spacecraft attitude. The measured deflection was 3.4°, which was close to the value inferred from the shift in the aerodynamic null. On the next orbit (#17) a similar technique was used to show that the latched panel did not bend at all, within the 0.5° accuracy of the Sun sensor measurement. On orbit# 18, a second measurement of the deflection of the unlatched panel produced the same 3.4° bending at a dynamic pressure of 0.19 N/m^2. Since the only explanation for the bending was that the solar wing was damaged more seriously than previously thought, the Project Manager decided to raise the periapsis altitude completely out of the atmosphere until the implications of the damage could be carefully considered. This decision to temporarily stop aerobraking was extremely serious, since it meant giving up the ability to reach the 2 pm Sun synchronous, 400 km circular mapping orbit for which the spacecraft was designed. It also meant that the remainder of the mission would have to be completely redesigned.

Damage Assessment During the Aerobraking Hiatus:

During the next 25 day hiatus from aerobraking, a very intensive analysis and ground test program was conducted to determine what failure would explain the panel deflection and what could be done to replan the mission. The most likely failure scenario that emerged from this hiatus was that one of the yoke facesheets had cracked when the undamped panel stopped abruptly during deployment (Figure 2). The yoke is similar in construction to the solar panels, with two graphite epoxy facesheets separated by an aluminum honeycomb. Ground tests and analysis both showed that the most likely failure was a cracked facesheet on the yoke, near the gimbal motor where the yoke is narrowest. The crack was believed to follow a stress concentration where the facesheet thickness was reduced from double to single thickness. Only the facesheet on the compression side (back side, see Figure 2) was believed to be broken because the graphite epoxy is not as strong under compression, and because the yoke used for ground testing broke on the compression side. The other facesheet is believed to be intact, and is providing the restoring moment that brings the solar wing back to the undeflected position after each drag pass. Further analysis and ground testing of a broken yoke at various load levels for many cycles resulted in a maximum acceptable dynamic pressure level of 0.6 N/m^2 for the thousand cycles that were needed to achieve a Sun-synchronous, 400 km circular mapping orbit at a reduced dynamic pressure. Of course, there was no way to guarantee that the damage to the flight hardware was the same as the damage to the ground test hardware or that the number of cycles placed on the ground test hardware was representative of the number of bending cycles that the flight hardware could survive.

Before aerobraking was resumed, a set of criteria were selected to enable the project analysts to determine if the panel characteristics of the flight hardware were changing in a way that would indicate a weakening of the yoke stiffness. These characteristics include the bending stiffness, which is inferred from the measured bending angle and the measured maximum dynamic pressure, and the natural frequency of the solar wing, which is measured by spacecraft attitude and acceleration perturbations using the inertial measurement unit. Both the stiffness and natural frequency will decrease if a crack begins to propagate on the undamaged side of the yoke. The return angle of the wing after each bending event is also monitored using the Sun sensor on the unlatched panel and compared to the return angle on previous orbits. These parameters are evaluated after each pass through the atmosphere, and contribute to the daily decision process for what is an acceptable level of drag for the coming orbits. The natural frequency attributed to the bending mode of the damaged wing, 0.166 Hz, has been relatively constant ever since launch. The accelerometer data showed that this 0.166 Hz mode is strongly excited on some orbits, as though the cracked edges might be suddenly slipping past each other while under compression from the aerodynamic moment. The return angle after each drag pass eventually returns to zero, but an unusual 1° bend was observed to build up sometime during the eclipse preceeding the drag pass during Phase 1 of aerobraking. This bending is believed to be thermally induced. The amount of bending during the drag pass has remained about 4° for a typical dynamic pressure of 0.25 N/m^2 near periapsis.

Mission Redesign During the Hiatus:

Since the original plan[4, 5] to achieve a mapping orbit with a 2 pm mean local solar time at the descending node required average dynamic pressures equal to the new "not to exceed" value of 0.6 N/m^2, and since aerobraking had been put on hold for one fifth of the planned aerobraking duration while the project analysts determined the extent of the damage, the originally planned 2 pm mapping orbit could no longer be achieved. After consulting with the Project Science Group (PSG), the Project Manager concluded that achieving a circular orbit was essential for meeting the mission objectives. The PSG selected a 2 am mean local solar time Sun-synchronous mapping orbit as the new target. The new mapping orbit is essentially the same as the originally planned mapping orbit, except that the Sun is near the ascending node rather than the descending node[6]. (To be consistent, the local solar time is still measured at the descending node.) Because the orbit plane precesses very slowly for orbit periods larger than 4 hours, the Local Solar Time (LST) changes as Mars moves around the Sun. Therefore, the local solar time of the mapping orbit is primarily determined by the date near the end of aerobraking where the orbit period drops below 4 hours, and the precession rate approaches a Sun synchronous rate. Thus the next opportunity for a 2 am orbit was early in February of 1999.

Aerobraking Resumed after the Hiatus:

Once the Project Manager decided that it was not only necessary to resume aerobraking to continue the mission, but also reasonably safe, a new plan was developed to reach the new 2 am mapping orbit target. Phase 1 of aerobraking resumed on November 8, 1997 on orbit # 37. The plan was to keep the expected dynamic pressure below 0.3 N/m^2 which maintains a 100% density margin relative to the redesigned dynamic pressure limits. A 100% margin was included in the original plan for random atmospheric density fluctuations.

Before reaching the new 2 am local solar time target, Mars passed directly behind the Sun at conjunction on May 12, 1998. Aerobraking could not be conducted while Mars was in conjunction, so a propulsive maneuver was necessary to terminate aerobraking in early May. (All of the propulsive maneuvers through the end of Phase 1 of aerobraking are described in a paper[7] by the Navigation Team.) The new mission plan took advantage of the opportunity afforded by the need to suspend aerobraking for conjunction by establishing a five-month period after conjunction for unique science observations in an elliptical orbit employing a very low periapsis, dubbed the Science Phasing Orbit (SPO). Low altitude (high resolution) imaging, Phobos imaging, targeted surface imaging, unique Electron Reflectometer and high resolution Magnetometer measurements were made possible by the SPO. The SPO phase began when periapsis was propulsively raised up out of the atmosphere on Orbit# 201 (March 27, 1998) when the orbit period reached the predetermined value of 11.5 hours about a month and a half before the communications blackout at conjunction. Targeting a specific orbit period was important for avoiding a resonance orbit, which could have resulted in large gravitational perturbations to the inclination.

Before conjunction, the MGS spacecraft collected science data, including targeted observations of high priority surface features, up to the point where commands could not be reliably sent to the spacecraft (April 28), at which point the spacecraft was put into a safe configuration until reliable communications could be restored after conjunction (May 28).

As the name Science Phasing Orbit implies, the instruments were turned on and pointed at nadir near periapsis to record science data that was played back later in the orbit when the High Gain Antenna was pointed at the Earth. During the pre-conjunction science gathering phase, some very interesting targeted observations of specific surface features were made. A link to a discussion of these observations can be found at http://marsweb.jpl.nasa.gov. The SPO carried the spacecraft through conjunction and continued to Orbit #573 on September 23, 1998, when Phase 2 of aerobraking began. The Mars Global Surveyor spacecraft will continue Phase 2 of aerobraking until about Orbit#1325 (February 9, 1999) when the periapsis altitude will be raised out of the atmosphere for the final time when the apoapsis altitude reaches 450 km.

Since the Attitude Control System uses between 5 and 10 grams of propellant on each pass through the atmosphere, and since the propellant budget is very tight, the project analysts had to minimize the number of aerobraking orbits. Since the 2 am mapping orbit is roughly determined by the date where Mars is on the other side of the Sun from the initial target date for the start of mapping, delaying the start of Phase 2 reduced the number of aerobraking orbits (and thus reduced the AACS propellant required for aerobraking) but increased the average dynamic pressure on each orbit. Even though Phase 2 started Sept. 23, 1998, one week later than planned, the average dynamic pressure will be less than the average for the latter part of Phase 1, so that there will be margin available in case there are unpredictable delays or greater atmospheric variability during Phase 2.

Table 1: Key Events During Phase 1 of Aerobraking

Orbit	Date	Altitude	Period	Dynamic Pressure	Comments
#1	9/12/97	262.9 km	45.0 hrs	0 N/m^2	Mars Orbit Insertion
#4	9/17/97	149.3 km	44.9 hrs	.004 N/m^2	First Drag Pass. Sun Crosses Equator into Southern Hemisphere.
#8	9/25/97	116.1 km	44.0 hrs	0.23 N/m^2	AACS Anomaly, No Telemetry.
#10	9/28/97	116.4 km	42.8 hrs	0.23 N/m^2	S/C Commanded to Contingency Mode to Reinstate Attitude Knowledge.
#11	9/30/97	111.2 km	42.2 hrs	0.49 N/m^2	0.2 m/s maneuver Panel Shifts 4° at Periapsis.
#12	10/2/97	110.5 km	41.0 hrs	0.53 N/m^2	Panel Shifts 15° at Periapsis Is Panel Latched ?
#13	10/3/97	110.3 km	40.0 hrs	0.64 N/m^2	Aeronull Still Offset, Bending ? 0.18 Hz Vibration Still Present.
#15	10/7/97	110.0 km	37.5 hrs	0.90 N/m^2	Unexpected 50% Density Spike Aeronull Offset => 17° Bending !?
#16	10/8/97	121.0 km	36.5 hrs	0.20 N/m^2	Periapsis is Raised. -X to Nadir for Bending Measurement of -Y. Sun Sensor Measured 3.4° bending.
#17	10/10/97	120.9 km	36.2 hrs	0.23 N/m^2	+X to Nadir, Panel Flipped for Bending Measurement of +Y. Sun Sensor Measured 0.0°
#18	10/11/97	121.2 km	35.7 hrs	0.19 N/m^2	-X to Nadir for Bending Measurement of -Y. (Still bending 3.4°)

#19	10/13/97	171.7 km	35.5 hrs	0.0005 N/m^2	Begin Hiatus. Periapsis Raised OUT of Atmosphere. Science Data is collected while analyses , tests, and redesign worked in parallel.
#37	11/8/97	134.8 km	35.2 hrs	.026 N/m^2	Resume Aerobraking "Phase 1" with first Walkin maneuver.
#41	11/14/97	124.4 km	34.8 hrs	0.16 N/m^2	Accelerometer Data shows unusual step followed by panel ringing with 6 sec period.
#50	11/26/97	123.5 km	32.0 hrs	0.14 N/m^2	Lower than average Dynamic Pressure. Lower Periapsis ? (It is not.)
#51	11/28/97	123.7 km	31.7 hrs	0.32 N/m^2	133% Increase in Dynamic Pressure signals Start of Dust Storm. Pair of Raise Maneuvers commanded.
#52	11/29/97	131.7 km	31.3 hrs	0.06 N/m^2	Density drops back close to what was expected.
#53	11/30/97	131.6 km	31.3 hrs	0.15 N/m^2	Density continues to Increase. A pattern of High and then Low densities develops that is eventually correlated to Longitude (wave 2).
#70	12/22/97	125.1 km	27.8 hrs	0.24 N/m^2	Dust Storm Effects have Disappeared.
#82	1/4/98	122.3 km	24.8 hrs	0.21 N/m^2	Start of Eclipse Region.
#85	1/7/98	121.1 km	24.0 hrs	0.26 N/m^2	Mars Perihelion. (Aphelion 12/17/98)
#110	1/29/98	120.5 km	19.3 hrs	0.30 N/m^2	1st MOLA Warming ISH Maneuver.
#114	2/2/98	121.2 km	18.8 hrs	0.21 N/m^2	First Draft of this paper completed.
#125	2/10/98	117.3 km	17.4 hrs	0.22 N/m^2	Maximum Eclipse of 58.1 min. 46.8% Depth of Discharge.
#132	2/15/98	117.1 km	16.6 hrs	0.31 N/m^2	Emergency APG to discuss Huge difference between peak density and average density. Peak Dynamic Pressure 0.452 N/m^2.
#141	2/21/98	116.1 km	15.7 hrs	0.41 N/m^2	Highest Dynamic Pressure in Phase 2 Accelerometer Peak = 0.483 N/m^2 7.7° Panel Deflection. Alarms Tripped.
#142	2/21/98	118.4 km	15.5 hrs	0.21 N/m^2	After Periapsis Raised by 0.148 m/s maneuver at apoapsis. Large Solar Wing "Ringing" on Orbit #143.
#194	3/23/98	119.8 km	11.7 hrs	0.16 N/m^2	Begin Reducing Dynamic Pressure to slow rate of period decay in order to hit orbit period target for SPO.
#201	3/27/98	125.1 km	11.5 hrs	0.05 N/m^2	Last Aerobraking Orbit in Phase 1.
#202	3/27/98	170.7 km	11.5 hrs	0.0008 N/m^2	First SPO Orbit.
#223	4/6/98	172.7 km	11.5 hrs	0.0003 N/m^2	Periapsis at North Pole. Target Pole with Mars Orbiter Laser Altimeter.
#268	4/28/98	174.1 km	11.5 hrs	0.0002 N/m^2	Begin Conjunction Seq. No Science.

#309	5/18/98	176.1 km	11.4 hrs	0.0002 N/m^2	Last Eclipse Orbit During SPO.
#329	5/28/98	176.8 km	11.4 hrs	0.0002 N/m^2	Resume Science after Conjunction.
#433	7/17/98	176.6 km	11.4 hrs	0.0002 N/m^2	Sun Crossed Equator Northward.
#573	9/23/98	171.1 km	11.5 hrs	0.0015 N/m^2	Last SPO Orbit.
#574	9/24/98	126.9 km	11.5 hrs	0.05 N/m^2	Begin Phase 2 Walkin.

Complications Created by the New Aerobraking Plan:

The operations team has faced many challenges due to the unplanned extension of aerobraking. The spacecraft was designed to operate in a 2 hour, Sun-synchronous mapping orbit around Mars. The maximum eclipse for the planned nearly-circular mapping orbit was only 40 minutes. Since the spacecraft is travelling much slower near apoapsis of the highly elliptical aerobraking orbit, the eclipses have the potential of being much longer than 40 minutes. In fact, the maximum eclipse duration of the first eclipse season in early February of 1997 was 58 minutes, 45% longer than the maximum design requirement. Surviving the eclipse meant that the solar panels had to survive very cold temperatures that nearly reached the requalification limits, in spite of the intensive effort to reconfigure and operate the spacecraft to maximize the panel temperatures at the entry into eclipse.

Another challenge associated with the longer than planned eclipse duration was the depth of discharge on the batteries. The batteries reached a maximum depth of discharge of 48%, which meant that the spacecraft would survive one battery failure, but the lifetime of the remaining battery would have been significantly reduced if one of the batteries had failed. Both batteries were still fully functional following the first eclipse season. The larger than desired depth of discharge means that the expected battery life has been slightly reduced, but not enough to jeopardize the planned 2 year (1 Mars year) mapping mission, which will put many cycles on the batteries when there is an eclipse every orbit. As long as aerobraking continues on schedule, the next maximum eclipse will be less than the 40 minutes that is typical for the mapping orbit. If the spacecraft does not reach an orbit period of about 6 hours before the next eclipse season, which begins near the end of Phase 2 of aerobraking, the maximum eclipse will be larger than 60 minutes, which would severely stress the spacecraft hardware. Thus, it is very important that aerobraking proceed as replanned.

Another operations complication due to the longer aerobraking phase is that the instruments could get too cold if the original aerobraking sequence were used. The instruments are located on the +Z face of the spacecraft, while the undeployed High Gain Antenna is mounted 90° away, on the +X face, as shown in Figure 1. During the original aerobraking sequence, the spacecraft would spend most of the time in "Array Normal Spin" (ANS), with the +X axis toward the Earth to maintain a high rate telecom link, and a 100 minute rotation about +X so the body-fixed Star Sensor can detect stars which are used to update the inertial reference. During the originally planned aerobraking phase, there was always some Sun available during part of the ANS rotation to warm the instrument deck. Since aerobraking will now take much longer to complete, Mars reached conjunction in the middle of the redesigned aerobraking phase, before the High Gain Antenna was deployed. Near conjunction, when the Sun and Earth are close together in the sky as viewed from Mars, the +Z face is in the shadow of the High Gain Antenna on the +X face (see Figure 1), so the instruments are not warmed by the Sun at anytime during the 100 minute spin. The on-board sequence was modified to include two inertial slews to tip the +Z face toward the Sun (and the +X axis, HGA boresight away from Earth) in order to keep the instruments warm.

Maintaining sufficient propulsive maneuver propellant has been another challenging task. The original plan did not have a very large propellant margin to begin with. The periapsis altitude has already been raised out of the atmosphere and then returned for the hiatus, and then raised out again at the start of the Science Phasing Orbit, and returned for the start of Phase 2. The ΔV budget contains enough fuel for only one additional periapsis raise / lower in case of an anomaly during aerobraking.

During Phase 2 of aerobraking, there is not enough time in the orbit to play back very much recorded science data, so the project analysts will have to use other means, such as the accelerometer and the Horizon Sensor, to detect the mission threatening atmospheric density increases that can accompany a global dust storm. Although Phase 2 occurs as Mars approaches aphelion, where global dust storms are believed to be less frequent, dust storms have been observed at every season on Mars, and will be a continued threat.

The New Aerobraking Trajectory:

The aerodynamic pressure at periapsis, $^1/_2\, \rho\, V^2$, is one of the most important aerobraking parameters. If the average dynamic pressure is too low, aerobraking will take too long and the spacecraft will not reach the desired local solar time for the mapping orbit. If the dynamic pressure is too high, then the spacecraft will be damaged. Figure 2 uses "+" symbols to show the dynamic pressure history (reconstructed by the Navigation Team) from Mars Orbit Insertion (MOI is Orbit# 1) through Oct. 4, 1998 (Orbit# 600). The events leading up to the hiatus that started on Orbit# 19 were discussed earlier. The most significant event during the remainder of Phase 1 was the dust storm that began around Orbit# 51.

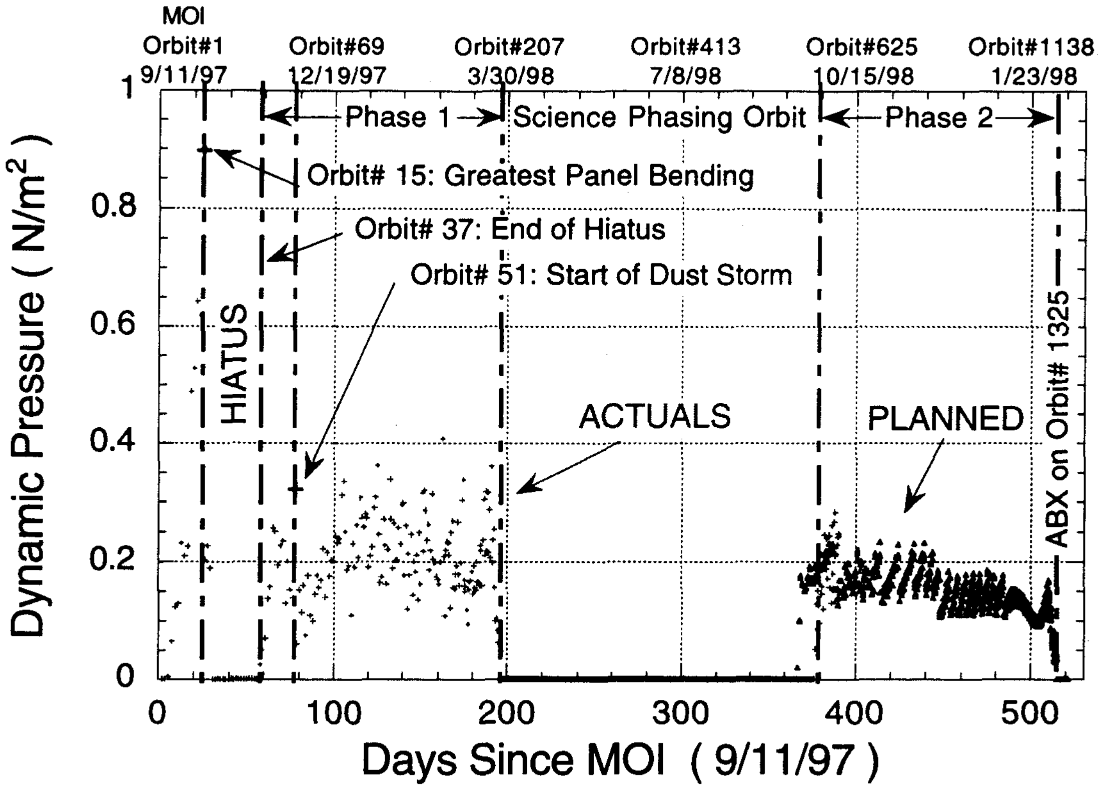

Figure 3: Dynamic Pressures at Periapsis: Actual and Planned

The primary reason that there is at least 100% margin on the expected dynamic pressure compared to the flight allowable is to accommodate both random variability in the atmosphere and the initially rapid monotonic density increases due to global dust storms near the surface. The periapsis altitude must be raised propulsively to accommodate the order of magnitude density increase that was predicted by prelaunch atmospheric simulations of the initial phase of a global dust storm by atmospheric scientists at the NASA Ames Research Center, the NASA Marshall Space Flight Center, and The University of Arizona. The simulations showed that the maximum density occurs only a few days after the start of a dust storm, because the high winds can quickly spread enough dust through the atmosphere to allow significant solar warming and expansion of the middle atmosphere, which increases the densities at a given altitude everywhere above the heated region. Thus, the project plans included an extensive observing campaign to monitor dust levels in the atmosphere of Mars during the aerobraking phase. These observations were particularly critical, because aerobraking had to take place during the so called "Dust Storm Season" centered on Mars Perihelion, where most large dust storms had been observed in the past.

On Orbit # 51, only fourteen orbits after aerobraking resumed following the hiatus, the atmospheric density increased by 133% from the value on the previous orbit. This increase was 4 times larger than the variability that had been seen up to that point. The magnitude of the large dynamic pressure increase triggered the procedure to command a normal "corridor control" maneuver that raised periapsis such that the expected dynamic pressure on the next orbit would be less than 0.3 N/m^2, even if the density remained at the unusually high value from the preceeding orbit. At about the time the periapsis raise maneuver was taking place, the dust observation data became available. The observations of the dust levels primarily from the Thermal Emission Spectrometer (TES) that was on-board the MGS spacecraft showed evidence of increasing dustiness. (These were later confirmed by the microwave observations made by Todd Clancy from the Kitt Peak Radio Telescope). Since the large density increase that had just been detected could be the start of a continued larger increase associated with the start of a global dust storm, the Flight Operations Manager wisely chose to increase the periapsis altitude even further with an extremely unusual second propulsive maneuver on the same orbit. During the next several days, the density increased by a factor of almost three before "gradually" returning to pre-dust storm levels. Both the rate of density increase, and the rate of decrease were more rapid than expected for a regional storm. Although the TES observations during the next month showed that the dust storm did not turn into the globally encircling kind that has the largest effect on the atmospheric densities, this regional storm in the southern hemisphere (centered on 30° South, 20° East) had a significant effect on the densities in the northern hemisphere near periapsis (at 35° North Latitude on Orbit# 51). In keeping with a longstanding tradition, this period of intensively exciting activity occurred on a holiday: Thanksgiving.

Following the start of the dust storm on Orbit# 51, the dynamic pressure was kept at a low value until there was definite evidence that the dust storm was dissipating. The sparse observations of previous dust storms indicated that dust storms could start up, begin to dissipate, and then start back up again, so the Flight Operations Manager remained cautious, and kept the dynamic pressure below planned levels until the dust storm was clearly dissipating. In order to make up for the slower rate of period reduction caused by the low dynamic pressures during the dust storm, the average dynamic pressure following the dust storm was increased from 0.20 to 0.25 N/m^2. By the time the dust storm dissipated, several techniques had been developed that enabled more accurate predictions of the dynamic pressure on the next orbit, which reduced the risk of a slightly higher average dynamic pressure. The most useful of these prediction tools was a correlation between the density and the longitude. Figure 4 shows a plot created by the creator of the MarsGRAM atmosphere model[8], Jere Justus, which shows the density ratio between the actual density at periapsis that was inferred from the accelerometer measurements and the density obtained from the MarsGRAM model. The wave 2 dependency on longitude is believed to be due to coupling of the strong polar vortex around the North Pole during Northern Winter and the topography in the Northern Hemisphere. (Early results from Phase 2 show a Wave 3 dependency on longitude, while the polar vortex has moved to the South pole.)

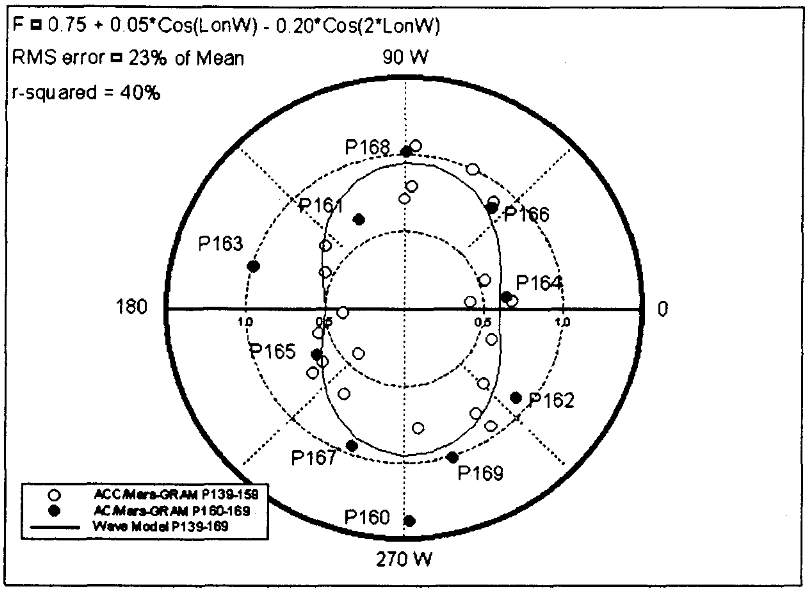

Figure 4: Density Ratio (Actual/MarsGRAM) vs Longitude

Figure 3 shows that the actual dynamic pressure ("+" symbols) was nearly zero during the Science Phasing Orbit (SPO). The spacecraft remained in the SPO until the middle of September, when periapsis was lowered back into the atmosphere. Figure 2 also includes the planned dynamic pressures { "Δ" symbols} up to the Aerobraking Exit Maneuver on Feb. 9, 1999 (Orbit# 1325). The dynamic pressures for the redesigned aerobraking phase are only about one-third to one-half as large as the 0.6 N/m^2 that was originally planned for the fully deployed solar panels, when aerodynamic heating was the primary constraint. Note that Phase 2 actually started 1 week later than the plan, because a ground software problem put the spacecraft into contingency mode a few minutes before the sequence was programmed to lower periapsis back into the atmosphere.

The sharp decrease in the dynamic pressure at the end of Phase 2 is due to a project requirement to maintain a 2 day orbit lifetime. The "lifetime" is actually defined by the time required to reach an apoapsis altitude of 300 km, which is 100 km below the mapping orbit altitude. The first time the orbit reaches the 2 day orbit lifetime constraint, the apoapsis altitude will be about 916 km. The spacecraft would be only one or two orbits from crashing if the apoapsis ever reached the 300 km apoapsis altitude "limit", so a 300 km apoapsis is representative of the orbit lifetime. When the orbit reaches the point where a 300 km apoapsis is predicted to be only 2 days away, periapsis will be raised by a 1.1 m/s maneuver in order to increase the orbit lifetime back to 3 days. One day later, the orbit will have decayed to the point where the orbit lifetime is again only 2 days, so another 1.1 m/s maneuver will be required. Trajectory simulations usually require 3 or 4 of these "Walkout" maneuvers before apoapsis has shrunk to the point (≈450 km) where the "Aerobraking Exit Maneuver" (ABX) can raise periapsis out of the atmosphere for the final time. The Walkout phase for the original aerobraking design was much longer, 12 days rather than 3 days, in part because the dynamic pressures at the start of the walkout phase were much larger. Using a 300 km apoapsis "limit" to define the orbit lifetime on the last aerobraking orbit is somewhat conservative in the sense of orbit lifetime, because the spacecraft would be able to survive for perhaps 12 more orbits beyond the 300 km apoapsis limit. Since the propellant required to get from the last survivable aerobraking orbit to the mapping orbit would be quite large, the 300 km "limit" has been used to indirectly limit the propellant cost in case there is a problem during the walkout phase.

The argument of periapsis drifts past the South Pole before the ABX maneuver is performed in all simulated trajectories that reach the desired 2 am mapping orbit. Since the desired periapsis location for the mapping orbit is at the South Pole, some time will be required for periapsis to drift back to the South Pole before the spacecraft can be propulsively locked into the Sun-synchronous, nearly circular, frozen mapping orbit.

The orbit period is another key aerobraking parameter. Aerobraking will shrink the orbit period from more than 45 hours at MOI to less than 2 hours at ABX. Figure 5 shows the past and planned orbit periods. The rate of decrease

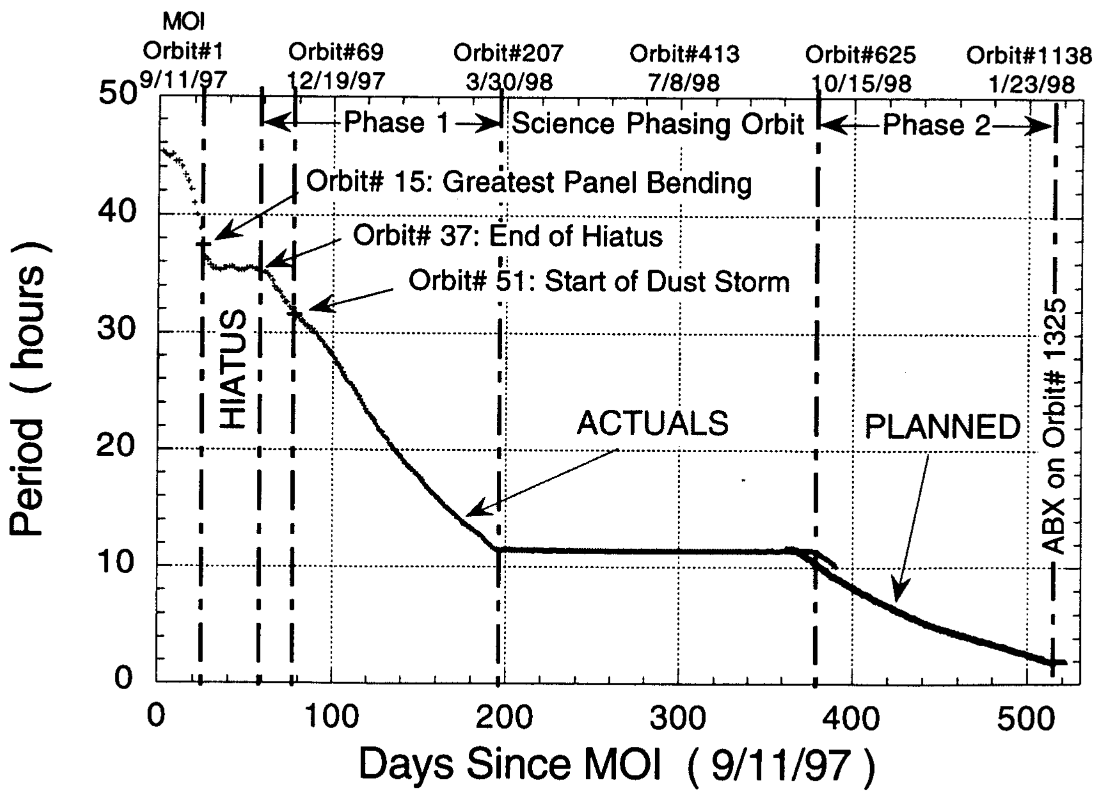

Figure 5: Orbit Periods: Actual and Planned

prior to orbit# 15 is much steeper than for the remainder, because the original plan used a higher average dynamic pressure to finish aerobraking in only 140 days. The amount of period decrease during the hiatus was insignificant. The rate of decrease during Phase 2 is expected to be slightly less than during Phase 1 because the planned dynamic pressures are less. Once the orbit period has been reduced to 1.89 hours, the ABX maneuver will raise periapsis out of the atmosphere.

The Mapping Mission:

When the Mars Global Surveyor spacecraft reaches the 400 km nearly circular, Sun-synchronous, 2 am Mapping orbit, it will begin a 2 year global mapping mission. The science instruments include the Magnetometer/Electron Reflectometer, the Mars Orbiter Camera, the Thermal Emission Spectrometer, the Mars Orbiter Laser Altimeter, and an Ultra Stable Oscillator for Radio Science observations. The spacecraft also carries a Relay antenna for use by future missions to Mars. All of the instruments, except the Relay antenna, have already made measurements of Mars. The purpose of the Mars Global Surveyor mission is to perform a global survey of the planet Mars. The Thermal Emission Spectrometer provides many spectral bands which will enable scientists to characterize not only the surface mineralogy, but also the atmospheric composition and temperature. A detailed topographic map will be produced from the Mars Orbiter Laser Altimeter data, while the Mars Orbiter Camera will provide a visual context using both wide and narrow angle cameras. Radio Science will produce a global gravity field as well as atmospheric profiles during occultations.

Table 2: Science Instruments and Investigators

Acronym	Full Name	Principle Investigator and Home Institution	Objective
Mag/ER	Magnetometer and ElectronReflectometer	M.H. Acuna Goddard Space Flight Center (GSFC)	Intrinsic magnetic field and solar wind interactions with Mars
MOC	Mars Orbiter Camera	M.C. Malin Malin Space Systems (MSSS)	Surface and atmospheric imaging
MOLA	Mars Orbiter Laser Altimeter	D.E. Smith Goddard Space Flight Center (GSFC)	Surface topography and gravity field studies
MR	Mars Relay Radio System	J. Blamont Centre Nationale d'Estudies Spatiales (CNES, France)	Relay Support for future Mars Lander missions, both American and International
TES	Thermal Emission Spectrometer	P.R. Christensen Arizona State University (ASU)	Mineralogy, condensates, dust, thermal properties, and atmospheric measurements
USO (RS)	Ultra Stable Oscillator for Radio Science	G.L. Tyler Stanford University (team leader)	Gravity field determination and atmospheric refractivity profiles

Details about the science observations can be found on the web through links from http://mars.jpl.nasa.gov/

Conclusions:

Aerobraking has enabled the Mars Global Surveyor mission to fit within the very tight budget available for the exploration of Mars by reducing the launch vehicle cost by at least 100 million dollars[9]. Aerobraking has proven to be a very robust option, enabling the mission to proceed toward what appears will be a fully successful completion, in spite of a major structural failure.

Aerobraking has also enabled new science observations at Mars that would not have been possible otherwise. Detailed measurements of the density and structure of the upper atmosphere have been made using the accelerometer that was originally used for precise propulsive maneuver cutoff. The extremely low altitudes required for aerobraking have enabled the Magnetometer to observe magnetic fields at a much higher resolution than will be possible from the mapping orbit, and enabled Electron Reflectometer measurements above and below the ionopause, something that will be impossible from the mapping orbit. During the hiatus, and the low-altitude Science Phasing Orbit, the narrow angle camera was able to take images at Sun illumination angles that are significantly better than from the Sun-synchronous mapping orbit. Targeted, high-resolution images of specific surface features were made during the SPO phase. Images, thermal spectra, and even laser altimeter measurement of Phobos were made near the end of the SPO phase.

Aerobraking has been a very exciting experience for everyone involved. A well thought out plan had to be significantly modified twice during flight by an operations team that was already much smaller than previous flight teams. A major structural failure and the resulting side effects of a greatly extended aerobraking phase were successfully accommodated. Dust Storms and the previously suspected but unknown atmospheric dynamics had to be overcome. The Mars Global Surveyor mission has been extremely challenging so far, and there is every reason to believe that Phase 2 will be just as exciting as what has taken place so far.

Acknowlegements:

The Mars Global Surveyor mission described in this paper has been a collaboration of many teams of scientists and engineers spread all across the country. The spacecraft was built by Lockheed Martin Astronautics, and the bulk of the spacecraft operations team is located at the LMA facility near Denver Colorado. The science instruments are operated by the Principal Investigators from their home facilities, which are listed in Table 2. Atmospheric monitoring and forecasting is provided by the Atmospheric Advisory Group, lead by Dr.

Richard Zurek (JPL). Observations are made by the on-board instruments as well as spacecraft telemetry measurements and ground based microwave observations. Spacecraft operations, including commanding, telemetry evaluation, subsystems performance analysis, and aerobraking sequencing, are performed by the spacecraft team lead by Kenny Starnes at LMA. A special team of students lead by Prof. Gerald Keating of George Washington University measure the atmospheric density and dynamic structure using an on-board accelerometer[10, 11]. The ground based microwave measurements from the National Radio Astronomy Observatory antenna at Kitt Peak are analyzed by Dr. Todd Clancy of the Space Science Institute. Atmospheric modelling is supplied by Dr. Jere Justus through the Marshall Spaceflight Center, Dr. Stephen Bougher of the University of Arizona, and by Dr. James Murphy and Dr. Robert Haberle of the NASA Ames Research Center. Interpretation of the TES observations are provided by a team lead by Dr. John Pearl at the NASA Goddard Spaceflight Center. Navigation is performed by a team lead by Dr. Pasquale Esposito at the Jet Propulsion Laboratory. Sequencing and ground data support are also supplied by JPL. The Mission Director, Joseph Beerer, and the Project Manager, Glenn Cunningham are provided by JPL.

Tracking and Commanding are performed using the Deep Space Network.

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